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Origin of Chondrites from Relationships

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Michael E. Lipschutz, Principal Investigator

Professor of Chemistry and Geosciences

Purdue University

West Lafayette, Indiana 47907

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I General Remarks

Since submission of our Fifth Semiannual Progress Report (September, 1973 - February, 1974) the following have been prepared for publication:

(1) "Trace Elements in Primitive Meteorites-V. Abundance Patterns of Thirteen Trace Elements and Interelement Relationships in Enstatite Chondrites," C. M. Binz, R. K. Kurimoto and M. E. Lipschutz, Geochimica et Cosmochimica Acta 38, accepted and in press (1974).

(2) "Thermal Metamorphism of Primitive Meteorites-I. Variation of Six Trace Elements in Allende Carbonaceous Chondrite Heated at 400 - 1000°C," M. Ikramuddin and M. E. Lipschutz, Geochimica et Cosmochimica Acta 38, accepted and in press (1974).

(3) "Allende Meteorite: Effect of Thermal Metamorphic Conditions on Mineralogy and Trace Element Retention," M. Ikramuddin, W. R. Van Schmus and M. E. Lipschutz, Science, to be submitted (1974).

(4) "R-Mode Factor Analysis on Enstatite Chondrite Analyses," D. M. Shaw, Geochimica et Cosmochimica Acta 38, accepted and in press (1974).

As noted in the Fifth Semiannual Progress Report, this last publication does not acknowledge NASA support but is based upon results of research supported by this grant.

The following talks based upon research supported by this grant have been presented since submission of the Fifth Semiannual Progress Report:

(1) "Thermal Metamorphism of Allende Meteorite," M. Ikramuddin, M. E. Lipschutz and W. R. Van Schmus, Fifty-fifth Annual Meeting, American Geophysical Union, Washington, D. C., April 10, 1974.

(2) "Abundance Patterns and Interelement Relationships in

Unequilibrated Ordinary Chondrites," C. M. Binz, M. Ikramuddin, P. Rey and M. E. Lipschutz, Fifty-fifth Annual Meeting, American Geophysical Union, Washington, D. C., April 10, 1974.

The following Ph.D. thesis on research supported by this grant was accepted by Purdue University:

(1) "Trace Elements in Enstatite and Ordinary Chondrite Meteorites," C. M. Binz, 154 pp. (May, 1974).

II Trace Element Studies

As discussed in the Fourth (March - August, 1973) and Fifth Semiannual Progress Reports, these investigations have proceeded along two major avenues: studying effects of thermal metamorphism of primitive meteorites; establishing the concentration of key trace elements in primitive chondrites and meteorites suspected of being derived directly from them.

A. Laboratory Studies of Thermal Metamorphic Effects

This avenue is one that had not been explored previously and upon which we are placing heavy emphasis. In the first paper reporting our experiments, paper (2) cited in part I, we report that determination by neutron activation of 6 trace elements retained in Allende (C3) samples heated at 400 - 1000°C for 1 week in a low-pressure (initially $\sim 10^{-5}$ atm) H_2 atmosphere reveals loss of small proportions of Ga and Se and large proportions of Bi, In and Tl - Co being unaffected. The retentivity patterns for the 5 mobile elements differ and in no way duplicate the step-function assumed previously. In contrast to these trace elements sulfur is initially present in discrete mineral(s) and visually it appears to be released over a narrow temperature range. Elements are lost more easily from powder than from chips but the difference is $\leq 35\%$. Above 600°C, the process of loss appears due to process(es) with apparent activation energies of 2 kcal/mole (Bi, Tl), 4 kcal/mole (Se) and 22 kcal/mole (In). Loss of Bi and Tl below 600°C involves higher apparent

activation energies. Two-element correlation diagrams involving Bi, In and Tl are consistent with the idea that trends among highly-volatile elements in enstatite chondrites arise from metamorphism.

In the second of our studies, paper (3) cited in part I, we report that heating Allende carbonaceous chondrite in a low-pressure environment causes mineralogic alteration at 700 - 1000°C but not at $T \leq 600^\circ\text{C}$. Samples heated for 29 days at 500°C lose Bi, In and Tl more effectively than those similarly heated for 7 days. At 1000°C with $\sim 10^{-5}$ atm. initial pressure of O_2 , H_2 or He these elements, Ga and Se are comparatively more completely lost. These results indicate the necessity for additional experiments in order to study elemental loss patterns in primitive objects.

Such studies are now in progress. We have nearly completed our measurements in an extended study of the Abee E4 chondrite in which we are determining 10 trace elements (Ag, Bi, Co, Cs, Ga, In, Se, Te, Tl and Zn). Thus far we have measured samples from runs at 400°, 600°, 700°, 800° 900° (2 runs) and 1000°. In the 900° case runs were made with and without a molecular sieve in the cold trap to investigate additional atmospheric effects. We plan an additional run shortly at 800° which will complete this portion of the investigation.

We have begun heating samples of BCR-1 to compare effects in this terrestrial high-temperature basalt with those in primitive meteorites. We have also obtained a large sample of an unequilibrated ordinary chondrite to extend our studies to these important primitive meteorites and we plan to start heating samples of this shortly.

As in our Allende study, in addition to trace elements, we are continuing to determine the mineralogic and petrologic characteristics of heated samples (Abee, BCR-1, etc.) in cooperation with Professor W. R. Van Schmus

of the University of Kansas. Examination of $^{18}\text{O}/^{16}\text{O}$ ratios in heated Allende samples by Professor R. N. Clayton of the University of Chicago revealed no measurable alteration from unheated samples. We are continuing to study the nature of the organic compounds generated during the heating of Allende samples in cooperation with Professor C. Ponnamperuma of the University of Maryland. Because of difficulty in obtaining suitable material we were not yet able to extend our studies to higher temperatures. However we have recently obtained material which we believe will prove suitable and we plan a pilot run at 1500°C to test this very soon.

B. Key Trace Elements in Primitive Meteorites

We have chosen to invest most of our research effort on the studies described in part IIA and, as a result, our progress in determining the concentrations of key trace elements in "as-received" (i.e. pristine) primitive meteorites has not been as rapid as it would otherwise have been. We have however revised our previous papers describing our studies of elemental abundance patterns and interelement relationships in enstatite chondrites. These papers have been combined and the combined version is now in press (cf. paper (1) in part I). We determined As, Au, Bi, Cd, Co, Cu, Ga, In, Sb, Se, Te, Tl and Zn in 11 samples representing 9 chondrites of grades E4-6. These chondrites exhibit systematic intra- and inter-grade differences particularly for highly-variable elements, the differences being $\text{E4} \geq \text{E3} > \text{E6} \geq \text{E5}$. The abundance pattern for these 13 and an additional 16 elements in E3-6 chondrites differs from those of other primitive meteorites - the carbonaceous and unequilibrated ordinary chondrites. A search for statistically-significant interelement relationships among the 13 elements (for grades E4-6) reveal that 40 element-pairs are linearly and/or exponentially correlated. Similar consideration of data for 37 elements in 12 chondrites (grades E3-6)

reveals that 191 element-pairs exhibit such relationships, 170 involving linear and/or exponential correlations, the remainder involving anti-correlations. The patterns depicting these relationships - i.e. the correlation profiles - and elemental abundance patterns, factor analysis and two-element correlation diagrams are consistent with all enstatite chondrites representing a single evolutionary sequence. The primary process responsible for the chemical trends of these chondrites involved thermal fractionation accompanied by geochemical fractionation of sulfide-plus-metal from silicate, probably during condensation and accretion of solid material from the solar nebula. Chalcophile elements may have been fractionated during condensation or, after accretion, during thermal metamorphism in the parent body. Indeed as described in paper (2) of Part I, the trends of Bi, In and Tl in "as-received" enstatite chondrites are consistent with those in heated Allende samples. No genetic model proposed thus far accounts for the detailed chemical trends although the constrained equilibrium theory and two-component condensation theories qualitatively seem most satisfactory. The correlation profiles of enstatite, carbonaceous and unequilibrated ordinary chondrites are distinctly different pointing to major differences in the formation conditions of these different sorts of primitive meteorites.

As mentioned, our data were supplied to D. M. Shaw and were used by him for factor analysis. These results are being published by him (cf. paper (4) in part I) and will appear simultaneously with our study of the enstatite chondrites.

As mentioned in the Fifth Semiannual Report, we planned to write up our studies of abundance patterns of these 13 elements and the correlation profiles in unequilibrated ordinary chondrites only after completing revision of our enstatite chondrite studies. We shall therefore begin preparing these data for publication very shortly.

We have also begun determining Ag, Bi, Cd, Co, Cs, Ga, In, Se, Te, Tl and Zn in ureilites and have completed measurement of 3 of the 6 known members of this class of meteorites. This study is aimed at answering the question of whether these meteorites were derived from carbonaceous chondrites by shock-heating. We plan on comparing the abundance patterns and two-element correlation plots of these elements in ureilites with those derived from artificially heated carbonaceous chondrites (as in part IIA).

III Other Studies

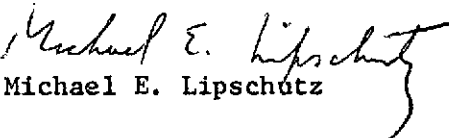
We are continuing our studies of shock effects in meteorites at a low priority level. In the case of Odessa meteorites (cf. Fifth Semiannual Progress Report) we have completed the shock studies; only a few more have to be measured for cosmogenic noble gasses by our co-worker, Professor G. Herzog of Rutgers University. We have also begun studies of nickel-poor ataxites to determine which have been thermally altered and under what circumstances this alteration occurred.

IV Administrative Information:

The following individuals are co-workers at Purdue currently doing research on this grant:

- A. Dr. C. M. Binz, Postdoctoral Research Associate
- B. Dr. M. Ikramuddin, Postdoctoral Research Associate
- C. Dr. A. V. Jain, Postdoctoral Research Associate (part time)
- D. Mr. S. Matza, Graduate Assistant in Research

The NASA Technical Officer for this grant is Dr. M. J. Smith, NASA Headquarters, Lunar Programs Office, Code SM, Washington, D. C., 20546.


Michael E. Lipschutz

cc: Dr. Bryson, NASA
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